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Holocene groundwater table fluctuations in a small perched aquifer inferred from sediment record of Kankaanjärvi, SW Finland

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Kankaanjärvi is a closed seepage lake controlled by groundwater flow within a perched aquifer. The results of this study indicate that its paleolimnological record forms a detailed groundwater table proxy covering the Holocene. Lake-level fluctuations were reconstructed from AMS-dated shifts in sediment properties, indicating marked natural changes of exceptional magnitude during the last 9000 years. The basin was more or less dry from 9000 to 6000 years ago. Since then, the water level gradually rose to its present limits of fluctuations about 3000 years ago. The record indicates that the water table of the associated perched aquifer is sensitive to precipitation changes, and that a decrease of 100 mm in annual precipitation may explain the low early Holocene level of the water system. The predicted climate change will likely keep the water table at a high, but stable level due to increased precipitation rates.

Introduction

Recent studies have produced more and increasingly precise information on Holocene temperatures in Finland (e.g. Heikkilä and Seppä 2003, Eronen *et al*. 2002, Ogurtsov *et al*. 2005, Weckstöm *et al*. 2006). The average temperature trend during the Holocene in southern Finland can be divided into three periods: the early warming phase (ca. 10 000–8500 cal. yr BP), followed by a more or less stable climatic optimum (8500–4500 cal. yr BP), and ending with a slow but continuous fall in reconstructed temperatures since 4500 cal. yr BP (Heikkilä and Seppä 2003). The information related to precipitation trends for the same period is derived mainly from studies of the wetness dynamics of raised bogs (e.g. Väliranta *et al*. 2007) or of the lake-level fluctuations of closed basins (e.g. Sarmaja-Korjonen 2001). This information is based on the observation that the water level in groundwater-fed lakes fluctuates with changes in palaeohydrology (e.g. Digerfeldt 1988). Vassiljev (1998) has demonstrated that lakes in humid climates are especially sensitive to changes in precipitation.

The lake-level data collected by Harrison *et al*. (1996) indicate that the overall climate in northern Eurasia was drier prior to 5000 BP, after which it gradually changed to modern conditions. Many studies (e.g. Digerfeldt 1988, Hyvärinen and Alhonen 1994, Barnekow 2000, Punning *et al*. 2005) from the circum-Baltic

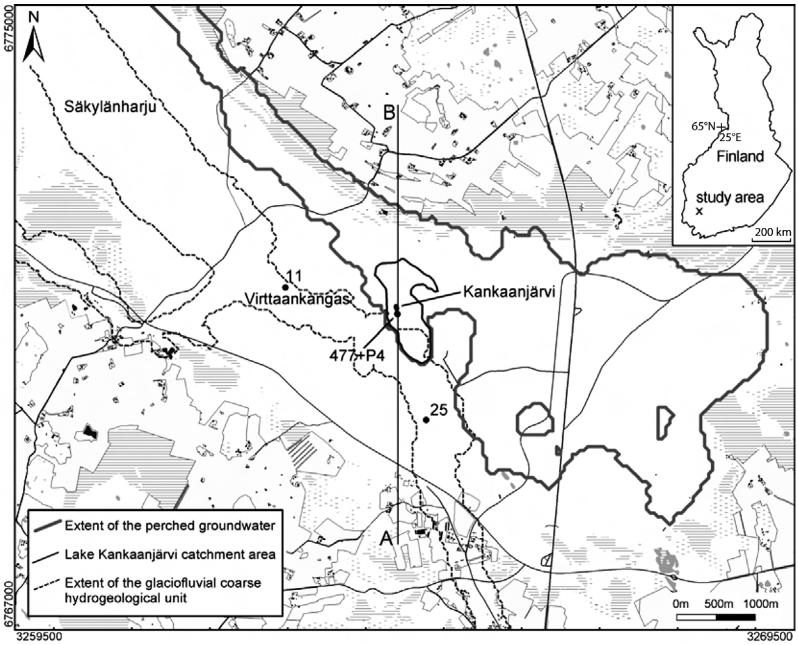

Fig. 1. The study area with kettle lake, Kankaanjärvi, and the lineation of aquifers within the Virttaankangas esker. Groundwater monitoring wells 11 and 25 are located in the main aquifer; monitoring wells 477 and P4 are in the perched aquifer.

region have verified this change. Rising lake levels since ca. 4500 cal. yr BP indicate a cool, more humid climate during the late Holocene. In Askola, southern Finland, the lake level rose to its highest stand only about 2500 cal. yr BP as cool, wet climate conditions began (Valpola and Salonen 2006).

Although groundwater is a direct product of climate, only a limited number of studies have explored the effect of climate change on groundwater levels (Kovalevskii 2007). Water-level fluctuations in closed water basins may be connected to long-term changes in the groundwater balance. According to Longmore and Heijnis (1999), sedimentary facies deposited within perched lakes react to any changes in water level, and hence to effective precipitation. The lakes serve as sensitive rain-gauges of the perched groundwater table. In some cases, Holocene trends in surface water and groundwater interactions have been coupled to a hydrological model; the studies of Vassiliev *et al*. (1998) and Cohen *et al*. (2006) are good examples of this. The results of these studies indicate that analysis of historical water table and lake level records provide information that can be modelled to demonstrate the historical recharge and water balance of aquifer systems. Hydrogeological modelling of a fluctuating groundwater table in the geological past may, in turn, provide quantitative information about the ancient infiltration rate (precipitation *vs*. evapotranspiration). This information could serve as a valuable additional proxy for paleomoisture reconstructions.

The Virttaankangas aquifer is one of the most important groundwater reserves in Finland. It has been intensively studied during the past two decades because of its planned use in the near future to produce artificially recharged groundwater for about 300 000 people (Salmi 1978, Anon. 1993, Artimo *et al*. 2003, 2007, 2008, Kortelainen *et al*. 2007). The main aquifer (Fig. 1) is hosted by a large Quaternary glaciofluvial complex (Mäkinen 2003). Sandy littoral deposits underlain by fine-grained glaciolacustrine sediments host several small-scale perched aquifers (Artimo *et al*. 2003), which recent data indicate are sensitive to climatic inputs: Exceptional drought during the years 2002–2005 led to a 3-metre drop in the water level in one of the perched aquifers and in the associated kettle lake, Kankaanjärvi. The lake recovered to its normal average level in the summer of 2008, after two years of normal precipitation conditions (Fig. 2).

The aim of this study is to compare lake-level fluctuations of a small, closed seepage lake and the water tables of the associated perched groundwater and of the deeper groundwater.

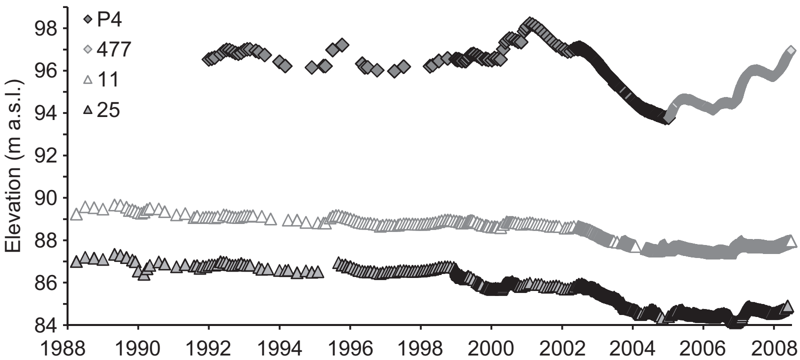

Fig. 2. Hydraulic heads of the selected groundwater monitoring wells. Wells P4 and 477 are located in the Kankaanjärvi perched aquifer. Wells 11 and 25 represent the hydraulic head changes in the main aquifer hosted by glaciofluvial deposits (units 2 and 3).

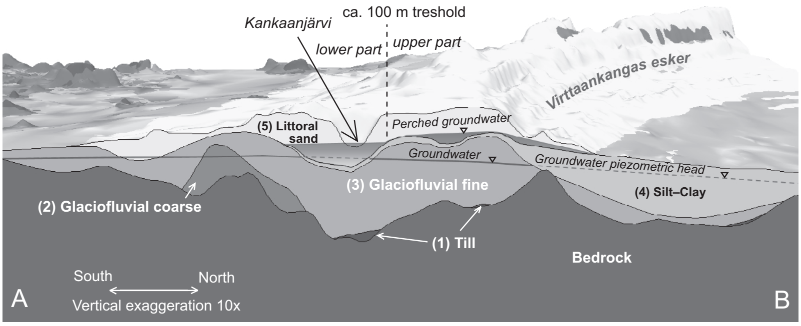

Fig. 3. A cross-section A–B (Fig. 1) displaying the main hydrogeological units and aquifers of the Virttaankangas esker. Upper and lower parts of the recharge area separated by the threshold at 100 m level are indicated.

Recent exceptional changes in the water balance will be quantified with a 3D hydrogeological model (Artimo *et al*. 2003, 2007, 2008) and compared with Holocene variations in the water table through paleolimnological analyses of the lake sediments. Evidence of the multi-proxy lithofacies (sediment texture, grain size and remnants of aquatic vegetation) proposed by Digerfeldt (1988) served to reconstruct former lake levels. The final goal is to assess future trends in the water balance of the Kankaanjärvi perched aquifer in the context of predicted climate change.

Site description

Kankaanjärvi is a kettle lake originating from the melting of a dead-ice block buried in the sand during deglaciation (Glückert 1971). It is situated in the Virttaankangas esker area in SW Finland (Finnish national grid 6771.102N, 3264.398E), which belongs to the EU Natura 2000 network of biodiversity conservation areas. The lake has an area of about 0.55 ha and is a closed groundwater seepage basin with no inlet and a high-water outlet over a perching glaciomarine/glaciolacustrine layer of silt and clay (Fig. 3). The current average water level is at 96.6 m a.s.l. The maximum depth of the lake is more than 7 m at normal water level stand (Fig. 4). Until the late 20th century, the lake sustained only minor human impact. *Pinus sylvestris* is the overwhelmingly dominant tree in the area, which belongs to the dry, *Vaccinium vitis-idaea*-type southern boreal forest.

The Virttaankangas area has an annual average precipitation of 630 mm yr^{-1} and temperature of +5 °C. The infiltration rate depends heavily on the soil properties of the area. Recharge rates are estimated to vary between 260–400 mm yr^{-1}.

The Virttaankangas plain is a 5-km-long, and 2–4-km-wide, fan-like enlargement of the Säkylänharju glaciofluvial ridge that forms part of southwest Finland's largest esker system, reaching from the Third Salpausselkä to the Gulf of Bothnia. The Säkylänharju–Virttaankangas complex formed between two retreating sub-lobes of the Scandinavian Ice Sheet (Punkari 1980, Kujansuu *et al*. 1995) during the late Weichselian glaciation. The average surface elevation of the Virttaankangas plain is

100–115 m a.s.l., and it gently dips towards the southeast. In addition to the shore cliffs and beach ridges, the plain includes one morphologically detectable kettle hole at 110 m a.s.l. (i.e. the basin hosting Kankaanjärvi) (Fig. 3).

The bedrock beneath the central part of the Virttaankangas plain comprises a major NS-oriented fracture zone 200–300 m wide and up to 100 m deep. The overlying Quaternary succession is well-documented by Mäkinen and Räsänen (2003), Mäkinen (2003) and Artimo *et al*. (2003); five unconsolidated hydrogeologic units have been distinguished (cf. numbers in Fig. 3). The Paleoproterozoic crystalline basement is discontinuously overlain by (1) a thin late Weichselian till blanket. The ribbon-shaped gravel unit consists of (2) the coarse-grained part of the esker, with a bouldery gravel core overlain by the sand and gravel deposits of overlapping glaciofluvial fans. The esker core is mantled by (3) a fine sand and silt unit related to glaciofluvial to glaciolacustrine deposition within a widening ice-marginal crevasse. The area was deglaciated ca. 11 000 years ago when the level of the Yoldia Sea was about 150 m above the current sea level. (4) The silt and clay unit tapers toward the south and represents glaciomarine/glaciolacustrine deposition in the Yoldia Sea and Ancylus Lake during the retreat of the ice margin. (5) The overlying sands and gravels are interpreted as spit-platform and shore-zone deposits, related to the littoral erosion of former glaciofluvial accumulations during the regressive Ancylus Lake stage in the Baltic basin from 10 800 to 10 000 years ago.

The main Virttaankangas aquifer system consists of glaciofluvial gravels and sands of units 2 and 3 in Fig. 3. The main aquifer has a total storage (S) of 150 million m^3 (Artimo *et al*. 2007). The natural groundwater recharge accounts for 43 000 m^3 d^{-1} in the entire 3D model area covering 80 km^2. The average hydraulic head within the main aquifer varies from 84 to 91 m a.s.l.

The littoral sand deposits (5 in Fig. 3) host several small-scale perched aquifers; the Kankaanjärvi aquifer (Fig. 1) belongs to the smallest of these (Artimo *et al*. 2007, Kortelainen *et al*. 2007). The Kankaanjärvi perched aquifer has a surface (recharge) area of 46 ha, a storage capacity of 1.09 million m^3 and an average hydraulic head at 96.6 m a.s.l. The perched groundwater table coincides with the level of Kankaanjärvi. No channelised surface water flows to or from the lake. Due to the high permeability of the sands hosting the lake, its water balance is governed by perched groundwater. The gradient of the hydraulic head indicates that groundwater flow enters Kankaanjärvi from the north and is discharged along the southern shore.

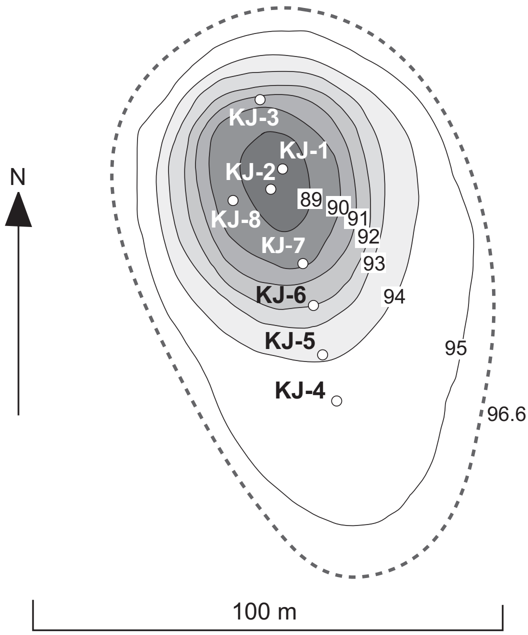

Fig. 4. Bathymetry and coring locations in Kankaanjärvi. The normal water level at 96.6 m is marked with the dashed line.

The difference in size and residence times between the main aquifer and the perched aquifers is reflected in the amplitude of the groundwater table fluctuations, which have been recorded since 1988 (Fig. 2). In addition to short-term fluctuations, the regional groundwater table has been in continuous decline since the late 1970s (Soveri *et al*. 2001). Because of its small volume, the perched aquifer is more vulnerable to changes in precipitation, evapotranspiration and run-off controlling the recharge. This can be evidenced by the three-metre drop in the water table following the dry springs and autumns of 2002–2005 (Artimo *et al*. 2007). Since the autumn of 2006, however, the water table has recovered quickly (Fig. 2).

Kankaanjärvi sediment record

Samples and analyses

Before coring, the bathymetry of the basin was mapped to a 50-m grid (Fig. 4). Based on the morphometry of the basin, sediment cores were recovered from the winter ice in March 2005 using a modified Russian peat corer with a 6-cm diameter; eight coring sites were selected to represent different depth zones and to obtain maximum variability of the sediment lithology. Cores KJ-1–KJ-7 were extracted from the lake basin along a NS-oriented transect, and core KJ-8 was extracted ca. 10 m west of core KJ-2 (Fig. 4).

The litostratigraphy of the cores was described in detail in the laboratory by identifying the grain size and structural components of the sediments. The sediments in two cores (KJ-2 and KJ-3) were further characterised by measurements of magnetic susceptibility (MS) with a Bartington MS2E1 surface scanning sensor at 1-cm intervals. In addition, the Munsell™ colour and loss-on-ignition (LOI) at 550 °C for two hours was determined from a number of subsamples representing various lithofacies.

The chronology is based on six ^{14}C Accelarator Mass Spectrometry (AMS) radiocarbon dates of terrestrial plant macrofossils (pine bark fragments) from cores KJ-2, KJ-4 and KJ-8. The dating samples were selected from deposits representing low water stand (e.g. the contact between the sand layer and peat or coarse detritus gyttja). Samples were treated in the Dating Laboratory of the University of Helsinki according to Slota *et al*. (1987) and then dated in the Uppsala Tandem Laboratory. The resultant radiocarbon ages were calibrated using CalPal software and the CalPal_SFCP_2005 calibration curve (Weninger and Jöris 2004) (*see* Table 1).

Description of cores

The average thickness of the lake sediments filling the Kankaanjärvi basin varied between four and five metres. The greatest recorded thickness, limited by the penetration of the corer, was 5.5 m (core KJ-8). Based on their physical characteristics, texture and macroscopic components, six main lithofacies were categorised (Fig. 5): (i) medium- to coarse-grained sand, (ii) peat, (iii) coarse detritus gyttja containing sedge-like plant material or abundant aquatic and emergent macrofossils, (iv) fine detritus gyttja, (v) faintly laminated gyttja, and (vi) black sulphide gyttja.

Most of the cores had medium- to coarse-grained, well-sorted, yellowish-brown sand at their bases (Fig. 6). The basal sand is typically massive and normally graded. In cores KJ-1, KJ-2, KJ-3 and KJ-8, sand facies also appear as thin interlayers in the lower half of the sections. These beds range in thickness from < 1 cm to 10 cm and show sharp lower contact with the underlying peat or coarse detritus gyttja. The KJ-2 section contained altogether eight separate sand layers; the uppermost was at a depth of ca. 85 m a.s.l. (Fig. 6).

Peat was observed in all cored sections except KJ-7 and KJ-8. The peat beds are typically 10–30 cm thick and composed of dark brown (Munsell 10YR 4/3) compacted mass consisting of sedge roots and seeds, moss tissue material and often also sand as single grains or as thin interlaminae.

Coarse detritus gyttja is the most abundant

Table 1. The uncalibrated (^{14}C yr BP) and calibrated (Cal. yr BP) AMS radiocarbon dates on pine bark fragments from the Kankaanjärvi cores

Lab code	Core ID	Sample depth (cm)	δ^{13}C	Age (^{14}C yr BP)	Cal. yr BP
Hela-869	KJ-2	277	–23.1	5410 ± 50	6197 ± 71
Hela-870	KJ-2	405	–27.3	8105 ± 70	9043 ± 129
Hela-871	KJ-2	350	–28.6	7540 ± 60	8313 ± 71
Hela-872	KJ-8	500	–24.0	6985 ± 60	7811 ± 69
Hela-873	KJ-8	515	–29.3	8185 ± 80	9162 ± 107
Hela-874	KJ-4	378	–27.9	7990 ± 65	8846 ± 118

lithofacies within the cored sections. It dominates the strata in the southernmost sections, and may reach 3.6 m in thickness (KJ-5). This facies contains seeds, moss tissue remains, leaves and other macrofossils. It is normally greenish-black (Munsell 2.5Y 2.5/1) in colour and has a loss-on-ignition of 50%–55%.

Fine detritus gyttja has an LOI of about 56%–64% and a dark olive-grey (5Y 2.5/1) colour. The sediment is homogeneous and contains only occasional remains of leaves or other plant macrofossils. Single grains of sand pepper the strata. Fine detritus gyttja is the most abundant facies in the deepest cores (KJ-2 and KJ-8) where the thickness of individual beds can be up to 1.8-m thick. Cores KJ-1, KJ-2 and KJ-8 (Fig. 6) are capped by ca. 50 cm of black, fine-grained sulphide gyttja that often shows faint lamination at the base. The sediment is loose, characterised by a high loss-on-ignition (60%–65%) and visible traces of gas ebullition.

The basal sand units and associated gyttjas can be correlated over short distances (e.g. KJ-2 and KJ-8; *see* Fig. 6). The lithostratigraphic variation in the basin mirrors the frequent water-table fluctuations within the lake system during its existence.

The magnetic susceptibility (MS) plot (Fig. 5) for core KJ-2 shows low values throughout the sections. The upper part (0–314 cm) of KJ-2 is characterised by uniformly low MS values (mean -0.14×10^{-6} SI) and very little scattering, except for peak values -11×10^{-6} SI at the 41-cm

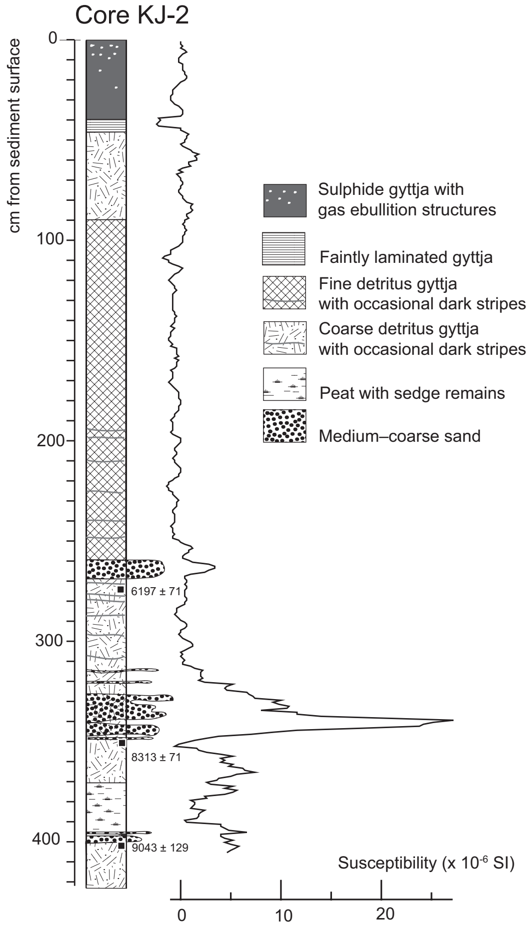

Fig. 5. Lithostratigraphy, magnetic susceptibility and age determinations of core KJ-2.

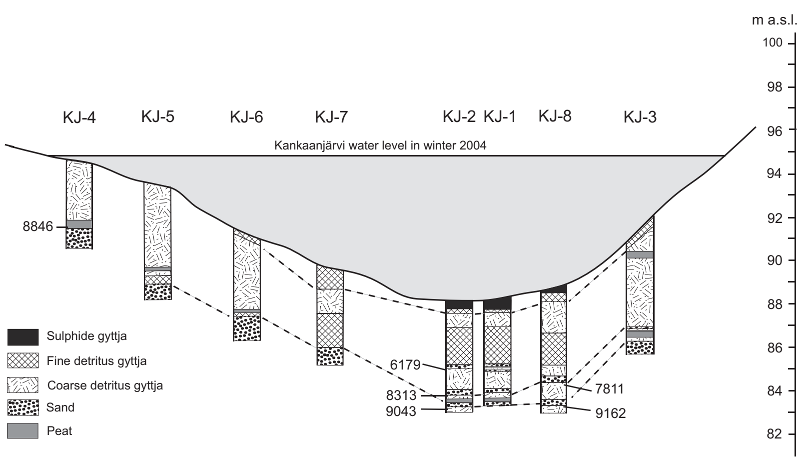

Fig. 6. A simplified sediment composition of Kankaanjärvi cores (KJ1–KJ8) and their correlation.

and 8×10^{-6} SI at the 264-cm level. In the basal part of the core (315–406 cm), the MS values are higher (mean 5.8×10^{-6} SI) but irregular, ranging between -1×10^{-6} SI and 36×10^{-6} SI. The susceptibility profile in KJ-2 corresponds well with visual observations of the sediments; the increasing MS values in the lowermost part are related to sand layers and detrital supply from the lake slopes. Values close to zero dominate the susceptibility record; these intervals have a relatively high organic matter content, which is diamagnetic with low negative susceptibility.

Discussion and conclusions

Paleolimnological development and lake-level fluctuations

Calculations of the shore displacement curves of the area (Glückert 1976, Donner 1995) reveal that Kankaanjärvi was isolated from the Baltic basin about 9600 cal. yr BP, within the transitional phase from Ancylus Lake to the Litorina Sea. The lowermost dated sediment yielded an age of 9160 calibrated years BP, thus indicating that the melting of the ice block and, hence, the build-up of the kettle hole was completed by about 9200 years ago, and that the studied sediments record a nearly complete history of the lake during the Holocene. The sediments that deposited in the kettle hole during its early stages prior to 9200 BP consist of sand. However, this was not possible to confirm with the coring device used in this study.

The lithological properties of the sediments show distinct variation, which indicates strong fluctuations in the lake level during the Holocene. The lowermost sands were probably washed to the basin at the same time as the ice melted and left the kettle hole. After that, evidence from peat and sand deposition suggests that the lake as well as the entire perched aquifer were nearly dry for the first 3000 years of their existence. The perched groundwater level began to rise at about 6200 cal. yr BP. Since then, regular small-scale fluctuation has occurred, but the kettle lake has never dried completely anew.

By modifying Digerfeldt (1986), and based on the remarks about recent sedimentation, we can assume that the observed sediment facies of Kankaanjärvi represent lake-level standings as follows:

- *Sand layers* can be connected to a very low level of the lake water and may represent short-lived deposition resulting from slope failures and associated grain-flow events. A sand layer indicates that the depth zone was close to the shore-line.
- A thin *peat layer* was observed to accumulate on the present shoreline at the southern edge of the lake at a water depth of less than one metre. Hence, peat deposition reflects the shore environment (max. 1-m-deep water) and relatively stable conditions. However, peat soils can also develop above the shore-line without direct connection to lake water levels.
- According the cored sections, *coarse detritus gyttja* is the surface sediment at a depth of one to four metres, thus bearing evidence of the intermediate water depth.
- In the cored section, *fine detritus gyttja* represents deep water (> 5 m) sedimentation.
- *Faintly laminated gyttja* and *sulphide gyttja* were found only in the deepest areas of the modern lake. The sediment properties indicate that the basal water in the deepest part of the lake nowadays suffers from oxygen depletion.

These ‘boundary conditions’ may further suggest that the observed and dated sediment sequences of Kankaanjärvi (Fig. 6) represent lake-level standings shown with a box-model for average water-level fluctuation amplitude in Kankaanjärvi during the last 9200 years (Fig. 7).

The lowermost gyttja in cores KJ-2 and KJ-8 indicates a relatively high stand of water in the initial phase. This phase was followed by a rapid drop in lake level; since then, all early Holocene lake levels fluctuated at a considerably lower level (85–88 m a.s.l.) than at present.

Around 6000 years ago, the lake level gradually rose to about 91–94 metres. Later, based on a steady sedimentation rate at about 2500 years BP, the lake level reached its present stand, where it fluctuates between 94 and 97 metres (Fig. 7). These results are in agreement with

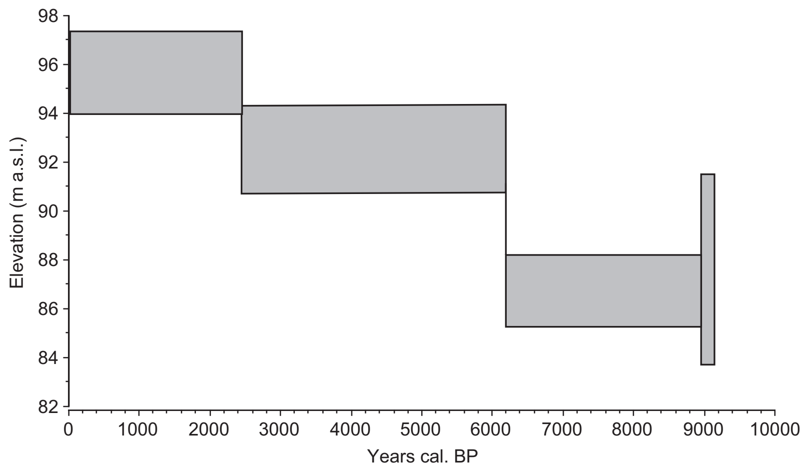

Fig. 7. Inferred fluctuations of Kankaanjärvi during the Holocene. The boxes indicate estimated amplitude of water level variations based on the sediment lithology.

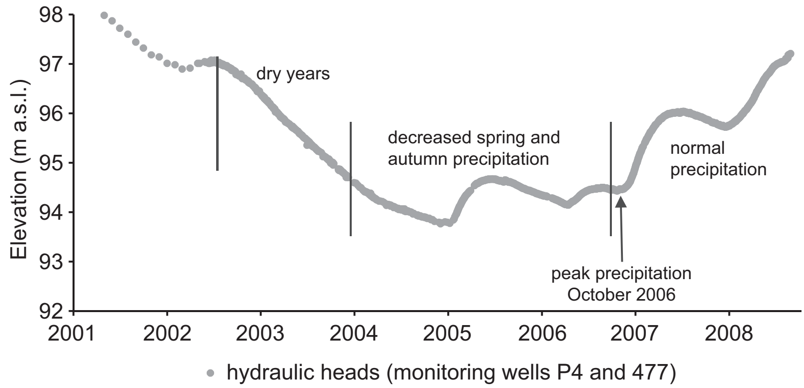

Fig. 8. Recent groundwater levels in the perched Kankaanjärvi aquifer. The most significant changes in precipitation are depicted in the graph.

other lake-level data around the Baltic Sea (e.g. Harrison *et al*. 1996).

Groundwater storage *vs*. precipitation

The climate record from the past 30 years may explain factors behind lake-level fluctuations. The average annual precipitation of the Virttaankangas area has been 630 mm yr^{-1} during the past 30 years (1971–2000). The years 2002 and 2003 were exceptionally dry with average precipitation rates of 511 and 542 mm yr^{-1}, respectively. The annual precipitation rates of the years 2004 and 2005 were close to the long-term average. However, the spring and autumn precipitations were significantly below the normal level during the years 2002–2005. Precipitation in the spring and autumn months contributes most of the annual groundwater recharge in southwest Finland (Soveri *et al*. 2001). This deficit evidently contributed to the decline in groundwater and perched groundwater levels during the four-year period. A clear departure from this trend occurred only after a peak precipitation of 152 mm/month in October 2006 (Fig. 8).

The water level of Kankaanjärvi coincides with that of the groundwater table in the lower part of the perched aquifer (Fig. 3). Using the hydrogeological model (Artimo *et al*. 2007) with the water table monitoring data, it is possible to calculate the storage capacity of the Kankaanjärvi perched aquifer at different water levels. The normal water level (96.6 m a.s.l) corresponds to a storage capacity of 1.09 million m^3. This storage capacity was only 640 000 m^3 when the water level was at 94 m a.s.l. In the early Holocene, the aquifer stored only about 100 000–200 000 m^3 of water (Fig. 9).

The relationship between precipitation and groundwater tables (Fig. 8) indicates that an annual decrease in precipitation of 100 mm

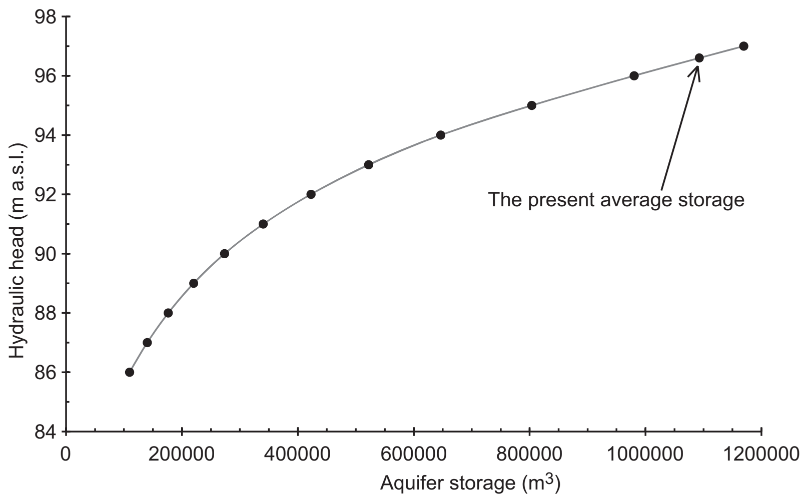

Fig. 9. The storage of the perched Kankaanjärvi aquifer at different water levels. The arrow points to the normal storage volume.

results in a 3-m drop in the water levels. The importance of precipitation during the winter half of the year (November–April) is apparent.

However, a drawdown of three metres cannot be explained by the observed decrease in precipitation as the only influencing factor. A major cause for the drastic changes in hydraulic heads in the Kankaanjärvi perched aquifer can be identified by detailed 3D mapping of the silt and clay unit supporting the perched groundwater. The recharge area of the Kankaanjärvi aquifer comprises two subareas (Fig. 3; Artimo *et al*. 2007), and their interaction depends on the relationship between the prevailing hydraulic head and the setting of the perching silt and clay unit between the two subareas.

The upper part of the recharge area contributes to the water budget of the lower part, which hosts Kankaanjärvi. In dry years, the threshold at about 100 m a.s.l. dried up, thus isolating the upper and lower parts of the recharge area. This led to an accelerated drawdown in the lower basin and Kankaanjärvi. Only after the peak precipitation of October 2006 was the groundwater flow connection from the upper recharge area re-established. The upper recharge area contributes about 40% of the total recharge of the Kankaanjärvi perched aquifer system.

Assuming that the recharge area of the perched aquifer is 46 ha, a simple calculation reveals that a decrease of 100 mm in precipitation results in a deficit of 46 000 m^3 in the annual water budget, provided the infiltration rate is close to 100%. If prolonged, such drop in precipitation could be enough to drain Kankaanjärvi almost completely, thus returning to a situation that evidently prevailed for the most of the early Holocene. This conclusion is in agreement with those of Vassiljev (1998), who demonstrated that precipitation changes alone can cause significant changes to the water tables of closed lakes in Estonia and southern Sweden. In Kankaanjärvi, the critical deficit required to permanently lower the water level seems to be about 100 mm in winter precipitation.

According to the doubling scenario for atmospheric CO_2, the predicted climate change is expected to raise the annual average temperature by 2 °C by the year 2020 relative to the mean of 1961–1990 (Jylhä *et al*. 2004). Precipitation is also expected to increase by ca. 10% during the same period. The scenarios show that warming will occur mainly at the expense of a rise in winter temperatures, when evaporation is negligible, thus emphasising the role of precipitation in groundwater recharge (Kovalevskii 2007). Thus, the low-water stand of the Kankaanjärvi aquifer will be a rare exception in the predicted future climate. Increased precipitation will result in increased runoff, for which increased outflow will largely compensate (Vassiljev 1998).

The sediment record of Kankaanjärvi and its associated perched aquifer form a sensitive ‘rain gauge’ to reconstruct in detail past changes in key climate parameters. It clearly promises the potential to complement the information gleaned from other related precipitation proxies such as the wetness development of raised peat bogs (Väliranta *et al*. 2007).

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